freedom
of form
foundation

Newsletter for December 2023

……

- Tail Project Summary
- Detailed Head Anatomy and Physiology

……

Tail project 2023 review part 1: hardware (the active electrode saga)

By Bleddyn and Nalco | January 2, 2024

Hello! In this article, we (Nalco and Bleddyn) would like to share the first part of our year-in-review series for the tail project. We'll be talking about our work on the hardware side of the project—specifically, our active electrodes.

Our last newsletter article in June 2023 laid out the premise and progress-to-date on our project as a whole. We are developing a prosthetic tail that the wearer can control naturally with the action of their own back muscles. To do that, we first need to build a testing platform where we can reliably measure the myoelectric signals generated by the muscles we're interested in using for tail control. Our other team member, Mecknavorz, has been developing software tools to allow us to record and view the muscle signals. Nalco and Bleddyn have been working on the hardware that actually does the recording.

To record muscle signals, we are using a technique called surface electromyography (sEMG). Our recording system is made up of a pair of electrodes that contact the wearer's skin above the muscle of interest, plus a third electrode placed away from the muscles that functions as a reference for the electrical signals. The signals from the electrodes are transmitted by wires to a pre-amplifier that outputs the difference of the two signals. From there, the resulting signal is converted from analog to digital and transmitted to a computer for analysis.

Early on, we had some success recording signals from our biceps muscles using a low-cost pre-amplifier (MyoWare 1.0) connected to a microcontroller development board (ESP32). However, we encountered problems with noise in the muscle signals from interfering electrical signals, from cable motion, and even from touching the cables with our fingers. To resolve these issues, we designed an "active" electrode that integrates additional pre-amplifiers in each of the two main electrodes (Figure 1). We decided to adapt our existing pre-amplifier to these new active electrodes with a custom "shield" (called the MyoWare Active Electrode Shield, or MyoAES) that connects directly to the MyoWare main board.

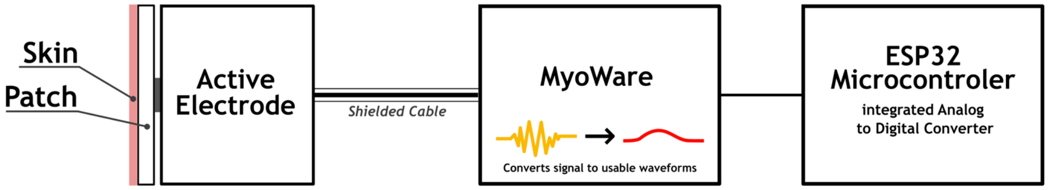

Skin
Patch
Active Electrode
Shielded Cable
MyoWare
Converts signal to usable waveforms
ESP32 Microcontroler
integrated Analog to Digital Converter

Figure 1: Block diagram of the tail project system for recording surface electromyography (sEMG) signals.

Those of you who saw our talk at Research Day 2023 might recall that our active electrode design was based on an open source schematic (available online), but adapted to the electrical requirements of the MyoWare 1.0 and miniaturized such that the entire printed circuit board (PCB) fits on top of one of the snap connectors that are commonly

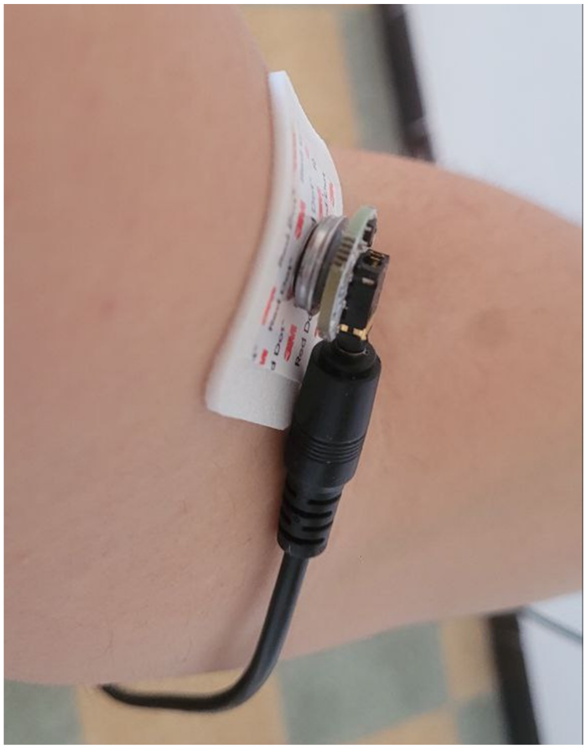


Figure 2: Photograph of an active electrode on Nalco's biceps.

found on medical adhesive patch electrodes (Figure 2). The circuit board is just large enough to incorporate a 2.5 mm TRRS jack, which allow us to detachably connect signal, power, ground, and shield from the electrode to the MyoAES.

Assembly

After ordering and receiving our PCBs and the associated components, Nalco embarked on the assembly process. We ordered our PCBs with a solder paste stencil, allowing us to complete the assembly ourselves rather than having the boards pre-assembled by the manufacturer. We chose this route to allow us to test our design at different stages of assembly. Additionally, given the small size of our electrodes, a single board from the manufacturer could actually fit 36 active electrodes. As a result, we were able to manufacture many electrodes at a low cost (Figure 3).

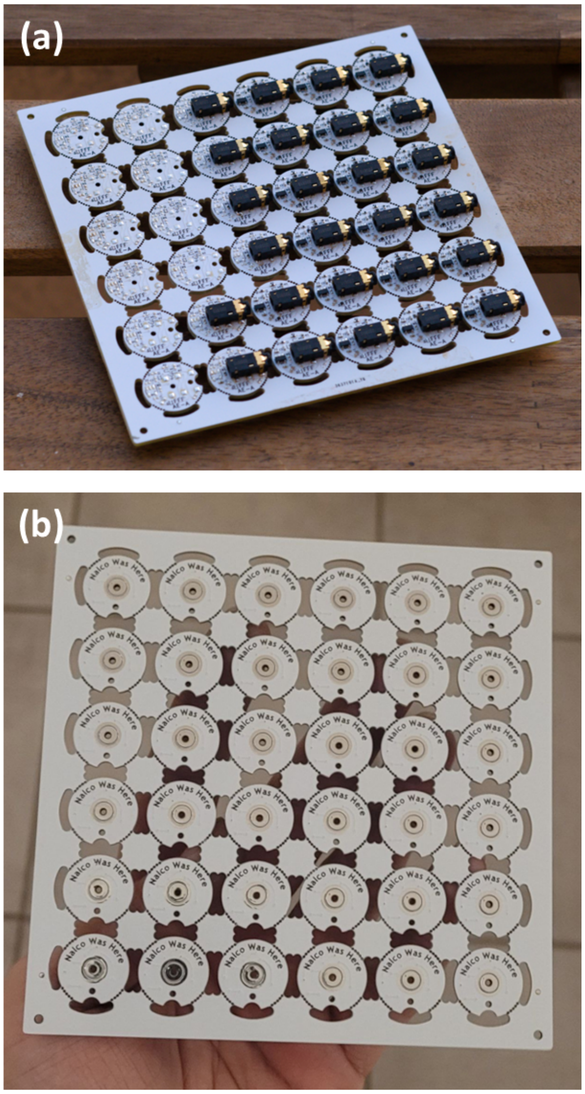


Figure 3: A panel of active electrodes under assembly: (a) front, (b) back.

To assemble the boards, Nalco used the stencil and squeegee to apply solder paste to the entire PCB. He carefully placed each component on its pad, a difficult and painstaking process as some of the components are only a fraction of a millimetre long with no identifying markings (Figure 4). Nalco reflowed the solder paste on a hot plate, melting the paste and permanently connecting the components to their pads (Figure 5). Inspection of the completed boards is critical to ensure that each connection was reflowed successfully. The snap connectors had to be soldered by hand onto the underside of each electrode.

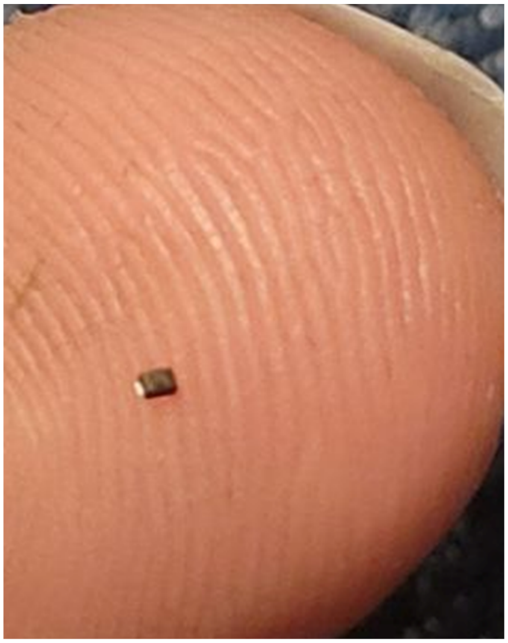


Figure 4: One of the diodes used on our active electrode PCB, perched on a fingertip.

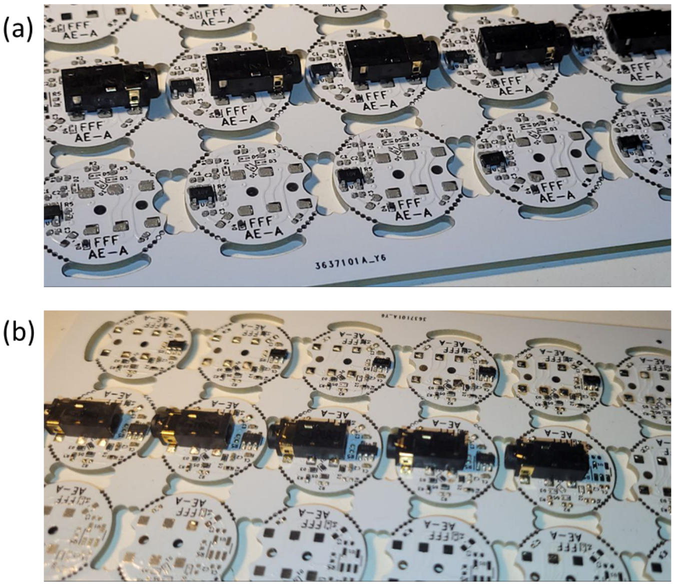


Figure 5: Photographs of the assembly process for our active electrodes. (a) Components are placed on a PCB panel after application of solder paste. (b) The same PCB panel after reflow soldering. Note the now-shiny solder on the pads.

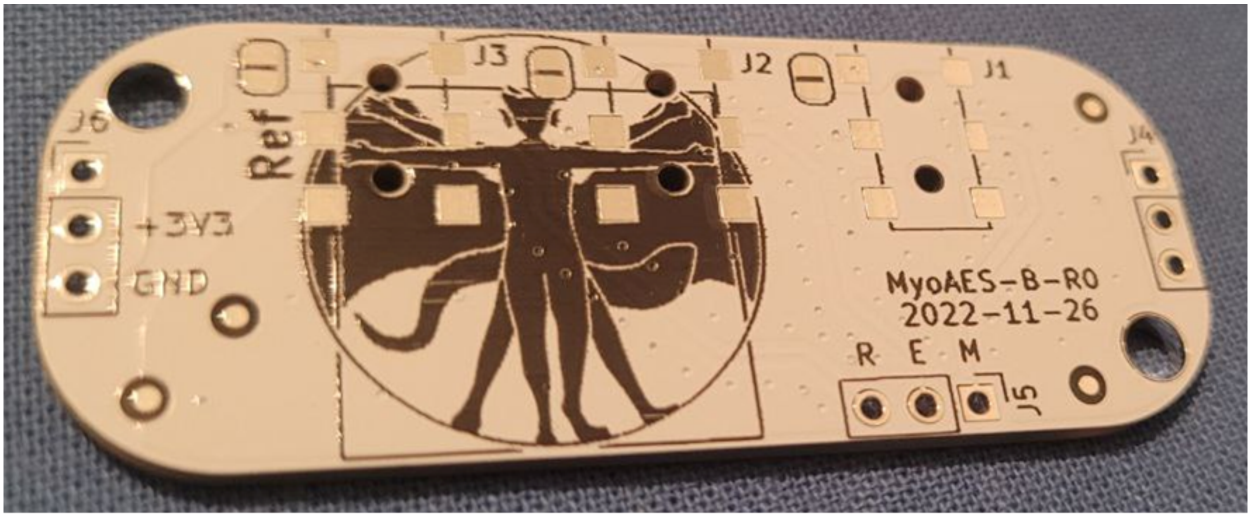


Figure 6: Photograph of the MyoAES PCB prior to assembly.

The MyoAES boards were assembled similarly, though with less difficulty as the components were all much larger (Figure 6).

Basic testing

Following inspection, it's a good idea to make sure the assembled device is functioning as expected. Nalco connected the input of the active electrode (the snap connector) to a signal generator that could output a known waveform. He then connected the output of the electrode to an oscilloscope. The electrode left the signal waveform unchanged, aside from raising the center of the signal from 0 V such that the minimum of the signal was 0 V instead, as designed. When the active electrodes are used together with the MyoWare, the center of the signal will be set to 1.5 V by the MyoWare's reference electrode, allowing for a larger swing of the signal between our "ground" potential and the supply voltage of 3.3 V (Figure 7).

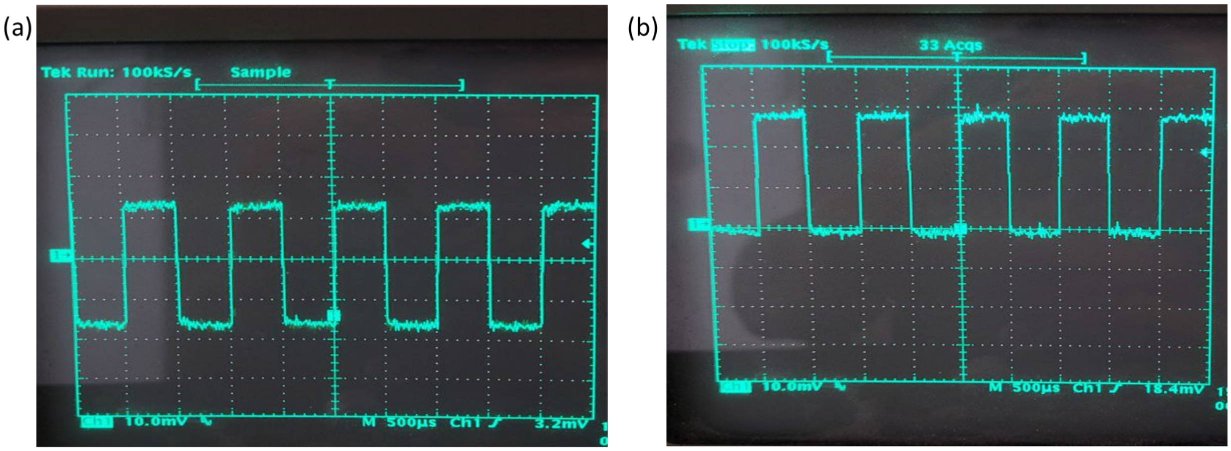


Figure 7: Oscilloscope traces from an active electrode under test. (a) A signal is applied to the input of the active electrode (1kHz 30 mV$_{pp}$ square wave centered on 0 V). (b) The resulting waveform at the output of the active electrode (1kHz 30 mV$_{pp}$ square wave with a minimum value of 0 V).

Testing with Olimex

Early on, the team had decided to purchase a "gold standard" reference system against which we could compare the performance of our active electrodes. We selected a commercially available, open-source and low cost pre-amplifier and analog-to-digital converter (EEG-SMT, Olimex, Bulgaria) with active electrodes (EEG-AE, Olimex, Bulgaria) designed for electroencephalography (EEG; measurements of electrical activity in the brain).

Using the EEG-SMT as designed with the EEG-AE, we found that we could easily measure biceps contractions with low levels of noise—a good indication that we were on the right track with our idea to use active electrodes. The system was even sensitive enough to pick up electrical signals from Nalco's heart—a good indication that he was alive at the time of the test.

Because our active electrode design was based on the design of the EEG-AE, we expected our electrodes to be compatible with the Olimex EEG-SMT. Nalco opened up the EEG-SMT enclosure and modified it so that it could be connected to our MyoAES board, which was then easy to connect to our active electrodes. Although the signal was noisier (around 10–20 times noisier; Figure 8), we were still able to observe biceps contractions with this setup. This was our first true indication that our active electrodes were functioning as designed, although it indicated that we may need to improve our shielding design to reduce what appeared to be interference from power lines (50 Hz in France, where Nalco performed this testing).

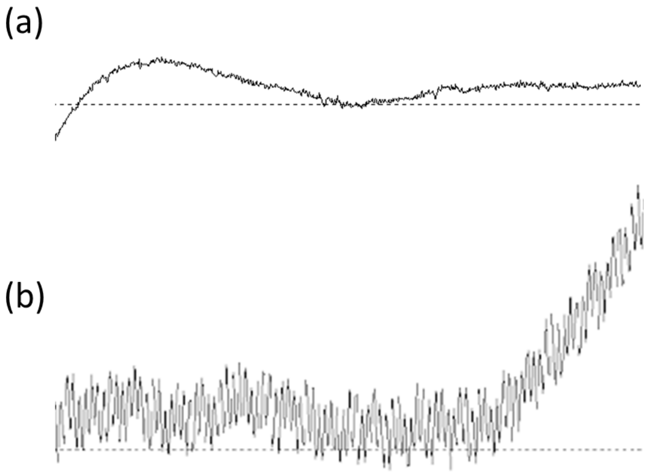


Figure 8: Noise test with sEMG traces of a biceps muscle at rest. Vertical units are arbitrary, and both signals share the same scale. (a) Olimex EEG-SMT with Olimex EEG-AE electrode. (b) Olimex EEG-SMT with our active electrode. In this test, the noise level of our electrode was 10 to 20 times greater than that of the EEG-AE.

Testing with MyoWare

Given that our electrodes were working as expected with the Olimex EEG-SMT, we jumped straight to testing with the MyoWare. This testing turned out to be more challenging than we expected.

We initially agreed that it made sense to have Nalco complete the testing of our active electrodes in France before shipping them to Mecknavorz and Bleddyn in North America. We discovered to our dismay that the MyoWare 1.0 had been discontinued in 2022, after we had purchased several for our team members and based the design of our MyoAES around it. The 1.0 version was replaced with a MyoWare 2.0, using a different form factor and upgraded components. We purchased one for Nalco in the hopes that it could be modified to serve as equivalent to the 1.0 for testing.

Given the difficulty of adapting the MyoWare 2.0 to the MyoAES board, Nalco worked to connect the active electrodes directly to the appropriate pins on the MyoWare 2.0. When this process was complete, however, we could not measure any signal from our active electrodes with the same setup that had worked with the Olimex EEG-SMT. We asked Nalco to try the MyoWare 2.0 with only passive electrodes—as it's designed—which required Nalco to solder extension cables between the electrode snaps and the electrode patches, given that the electrode patches we purchased were too large to fit side-by-side on the compact body of the MyoWare 2.0. This did not work either.

With all of these modifications, we suspected that the MyoWare 2.0 had become damaged, or perhaps was defective, so we purchased a second MyoWare 2.0 for Nalco to test. Unfortunately, this unit didn't give us any measurable signal either. Changing the gain on its amplifier had no effect, and the output signal from this MyoWare appeared to be saturated with no obvious source. We were mystified, as neither Mecknavorz nor I had had this issue with our MyoWare 1.0 units. Nalco even tried adding insulating tape to the bottom of the MyoWare 2.0, as exposed vias on the bottom of its circuit board were contacting his skin, but this didn't help.

Given the strong power line noise we observed when using our active electrodes with the Olimex EEG-SMT, we suspected that electromagnetic noise in Nalco's apartment could be interfering to such an extent that it was saturating the amplifier on board the MyoWare. Nalco purchased a USB isolator and connected the MyoWare 2.0 with this isolator to his laptop (which runs on battery power) to isolate the system from utility power. In this configuration, he was able to measure biceps contractions successfully with the MyoWare 2.0 and passive electrodes! In retrospect, it seemed that the MyoWare 2.0 didn't like being connected to his desktop PC, which due to the wiring in Nalco's apartment, was not connected to the utility ground.

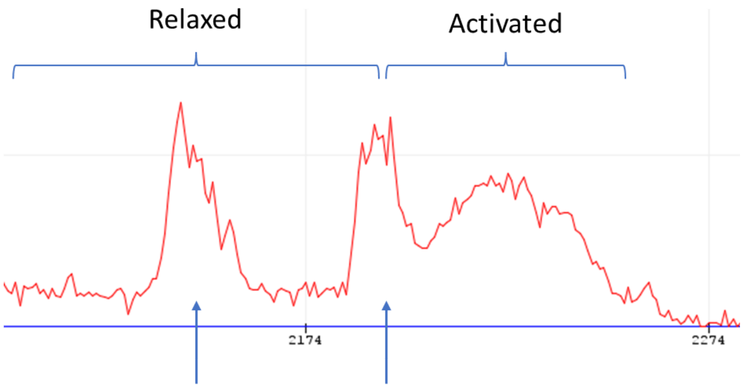


Figure 9: sEMG trace of Nalco's biceps muscle using the MyoWare 2.0 and passive electrodes. Brackets above indicate muscle relaxation and activation. Arrows below indicate artifacts where the adhesive electrode patch was pulling away from the skin.

Mechanical issues

Our success with the MyoWare 2.0 revealed further challenges with the mechanical design of our system. Early in 2023, we attributed some of our problems to the fact that Nalco's first batch of electrode patches (Red Dot 2560, 3M) appeared to have a conductive gel core that had partially dried out. A second batch we purchased were better, but frequently came unstuck in the hot environment of Nalco's apartment, causing signal artifacts that were obvious once the MyoWare 2.0 was working properly. Although heat and sweat were factors, the comparatively large and heavy shielded TRRS cable appeared to exert a moment arm on our tiny active electrodes, causing the adhesive electrode patches to break contact with the skin (Figure 2). We discussed methods for using medical tape to support and secure the electrode assemblies. These methods did not seem to help much until we learned that 3M also manufactures sweatproof versions of their electrode patches (Red Dot 2238). Nalco will use these patches for all future testing.

Next steps
After seeing the additional time it took to resolve these issues, our team agreed to prioritize the shipping of a share of our active electrodes to each of Mecknavorz and Bleddyn. This will allow the team to pool our efforts on any further troubleshooting required to get our hardware working.

Meanwhile, Nalco has already brought forward several ideas to improve the design of our sEMG measurement system. Given his skill with circuit and PCB design, and the incredible miniaturization of integrated circuits, it may be feasible to build most of the sEMG pre-amplifier into each electrode, reducing the need for the heavy shielded cables used in our present design. Even small changes, like widening the hole where the electrode snaps attach to the electrode circuit board, would allow the electrode assembly to sit closer to the skin and reduce the pulling that causes patch peeling.

—

When it comes to research, things rarely proceed as planned! We on the tail project team were reminded of this frequently over the past year, especially when it came to work on our active electrodes. That we overcame these challenges has demonstrated the value of our team's persistence. We'll be back soon with more news on the software side!

We thank FFF staff, volunteers, and the community for their support. The equipment used in this work was paid for by FFF donors.

Detailed Head Anatomy and Physiology

By Zennith | January 2, 2024

In our November 2023 newsletter, I mentioned we were working on an ambitious head anatomy video (series). That work is going nicely - we got a script for the first video complete, and we even got it done before our goal of December 18th! We've also made the decision that this will indeed be a video series, because the first video will already be over 30 minutes long. In January of 2024, we're aiming to finalize the visualizations in the video, and we're aiming for a February release. So, things are on track.

The underlying work on this video is turning out to be more useful than expected. Compared to our modeling work in 2022, our modeling revisions this time are more meticulous, and our conclusions are getting more precise and actionable.

This modeling work is the focus for this newsletter article - it's fascinating!

Modeling individual bones in the head
For starters, last year, we had developed bone models of human, wolf, and dragon skulls in Blender. The human skull was assembled from individual mesh objects corresponding to each individual bone, sculpted from general anatomy references. Then, we morphed those models to approximate shapes needed for wolves and dragons. Some details of this analysis are written in our June 2022 newsletter. We learned a lot about the anatomy and physiology, and built a general understanding of the types of modifications needed for each bone while preserving function of the physiology.

In that analysis, we were also comparing head shapes to available medical imaging scans of skulls, such as publicly available scans online, and a scan of my own head that I've had laying around. The value of real imaging scans is that, unlike general anatomy references, you can be confident that the exact proportions and shapes are true, rather than simplified or erroneous in some way.

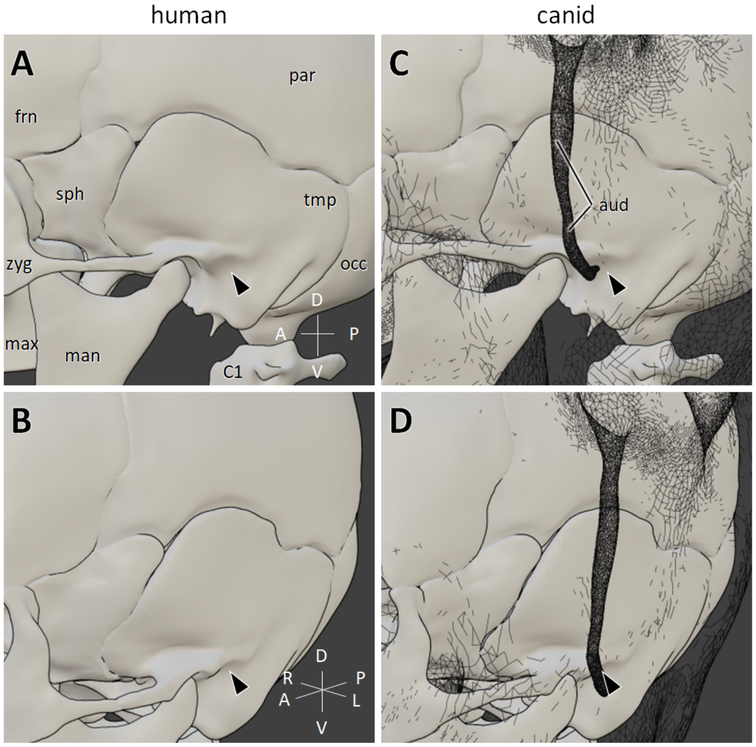
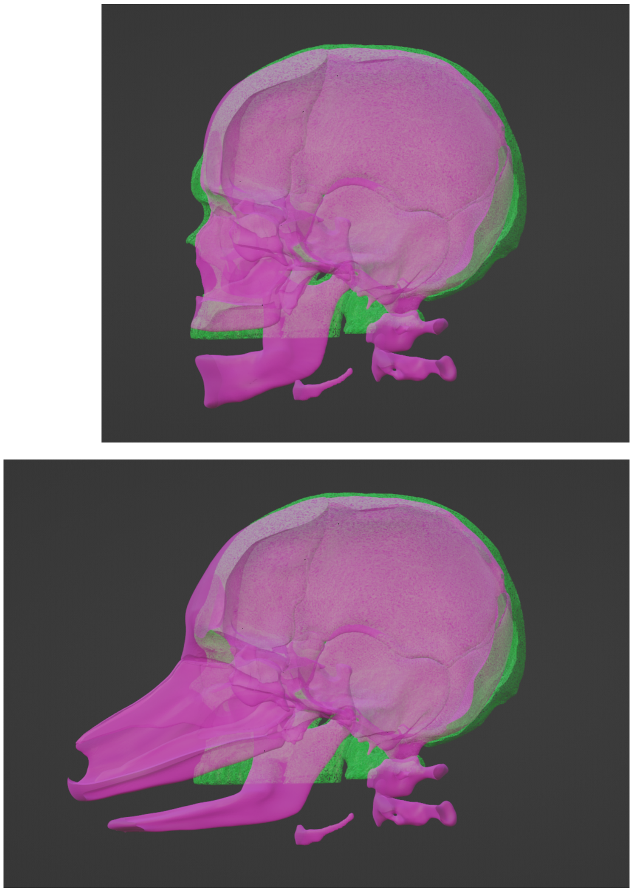


Illustration from 2022 of how a vertical auditory canal would allow canids like wolves to have ears appear on top of their heads while their inner ears are near the bottom of their temporal bones. This is similar to the vertical auditory canal in quadrupedal canids.

By comparing real imaging scans to our models, we were happy to reach a really important conclusion, that modifying the shape of the braincase is unnecessary to get a great head shape for an anthro. We wouldn't have to worry about the head appearing to be too round, nor about squishing that important thinking-jello in your head.

Many of the other conclusions also stand up to time: we'll need a longer maxilla, mandible, vomer, and ethmoid plate. The frontal bone's anterior edge will need to be advanced forwards. The orbits probably need to be spaced further apart laterally. And, interestingly, the vertical auditory canal for the ears means that your inner ear can stay where it is - safely inside the bottom of the temporal bone - even if ears appear to be on top of the head.

But, there were also some specifics with our bone models that didn't line up with the medical imaging scans - so there were possibilities that some preliminary conclusions were still based on incorrect assumptions or modeling. For example, we were left wondering whether or not the

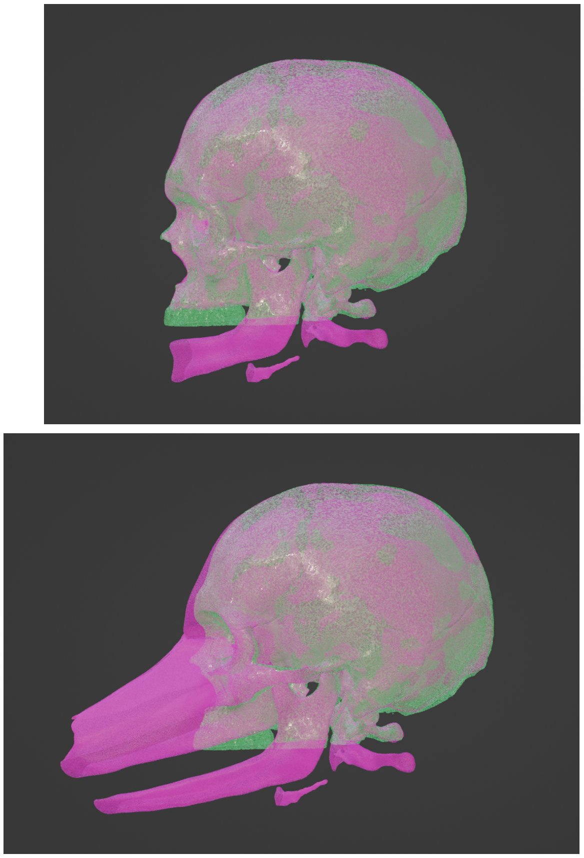


Overlay of modeling from 2022. The magenta objects are our models of individual bones based on anatomical references. The green object is a real CT scan of my own head. While the braincase and orbit positions align well - supporting our conclusion of the braincase not needing modified in anthros - other areas don't align well, namely the maxilla as well as cervical vertebrae.

pharynx would need to be compressed in some way, since its vertical size appeared to be smaller in anthros. We were hitting the limitation of our models at the time.

This is painstaking work and we ran out of time for the task, so we just had to set it aside and come back to it at a later time. Well, we've come back to it! Needing to get everything accurate for this video - a higher bar than internal planning purposes - has been a great motivator.

So, I went back into the individual bone meshes and matched each one to my own CT scan. With the exception of the lower portion of the mandible, most of the C2 vertebra, and all of the hyoid, the rest of the bones in our human skull model are now tightly matched to real data. Due to asymmetries present in all real skulls that are not expected to be impactful on conclusions, we modeled based on the left side of my CT scan and mirrored it to the right. As you can see by how well the models align now…much better!



Overlay of updated models from late 2023. Color scheme is similar to previous page. The braincase and orbit positions align well, as do the maxilla and cervical vertebrae.

Precise bone modeling and physiological implications

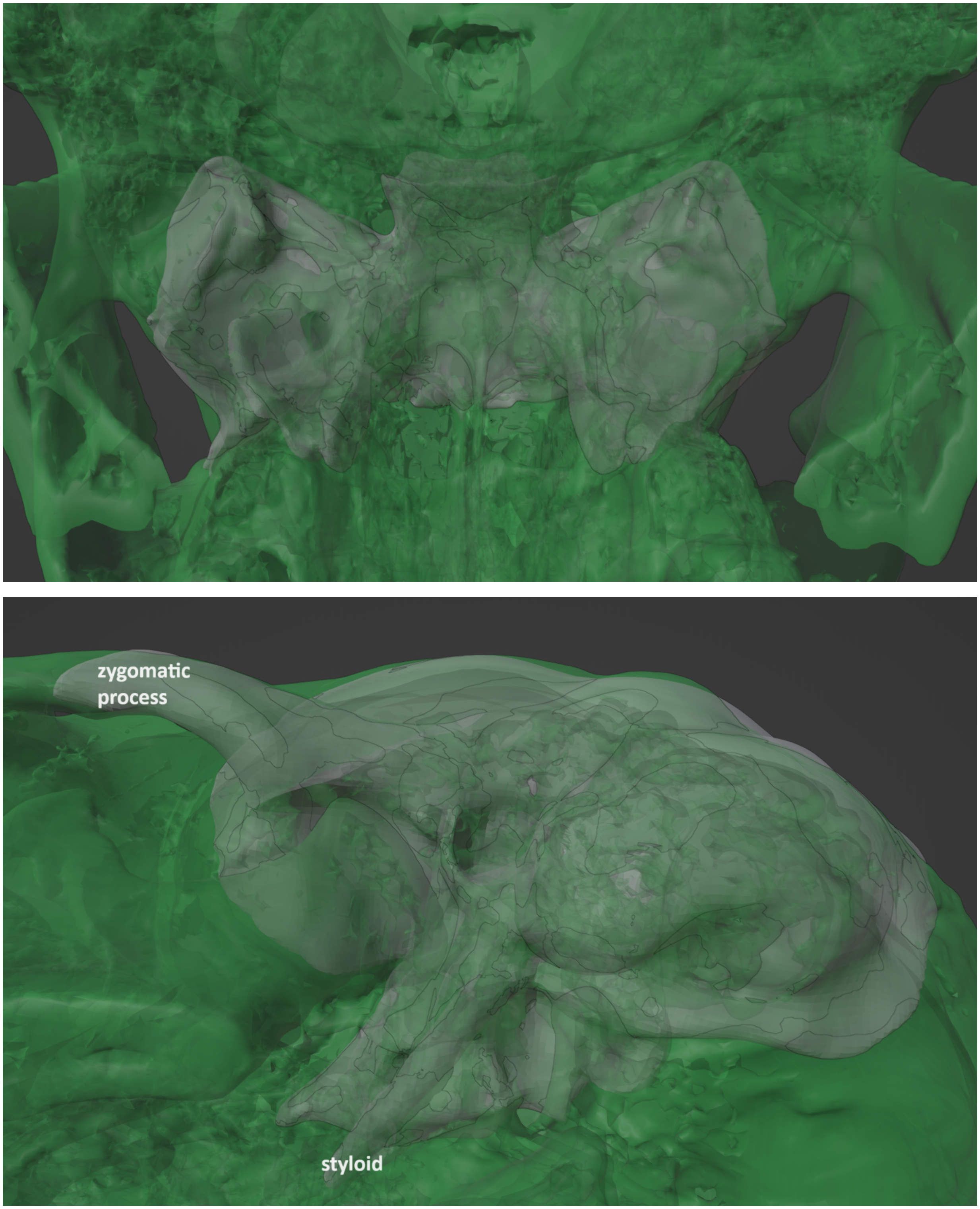
Getting to an accurate and precise model is valuable - getting closer to what real biology already does successfully - because you can be more confident that an anthro's physiology based on that model will work as intended.

Though, looking at the sides of heads only tells you so much. So, let's go into some more detail. Namely, the underside of the braincase, formed by the sphenoid, temporal, and occipital bones. The undersides of those bones attach to many muscles in the oral cavity, neck, and spinal column, and many nerves, blood vessels, ducts, and passageways including the airways pass through the area. By carefully matching our model to the data, we can be sure that our model is properly representing the space and surfaces required for all the physiology happening in the area.

Due to the complexity of the area, we would prefer to avoid modifying it if we can. That's not a hard-stop if we had to modify the area (unlike inside the braincase, which *is* a hard-stop at this stage of technology). But, any modifications to the underside of the sphenoid, temporal, and occipital bones would have to be justified due to the greater demands on research and surgical techniques.

In 2022, while our model at the time was at the limit of its applicability, the anthro's proposed bone shapes made us wonder whether the underside of the sphenoid would need modified, potentially impacting at the airways and pterygoid muscles, and would need to maneuver around eustachian tubes, salivary ducts, and the facial nerve, with any such modifications having to occur in a confined space.

Thankfully, our late-2023 model update has gone a long way to providing the necessary resolution to answer the question. It successfully matches available data - check out a couple examples on the next page.



Comparison of CT scan data and our modeling of individual bones. CT scan data is in green, and our model bones are in gray. Meshes are partially transparent to visualize overlap.

Top: *View from the underside of the head, showing sphenoid bone. The maxilla is towards the bottom of the picture. The left side of the head is on the left side of the picture.* ***Bottom:*** *View from the underside of the left temporal bone. The maxilla is towards the left of the picture. Zygomatic and styloid processes are labeled.* ***Both:*** *Our model corresponds nicely to data for these bones. Similar-quality matches were obtained for all other bones with data present.*

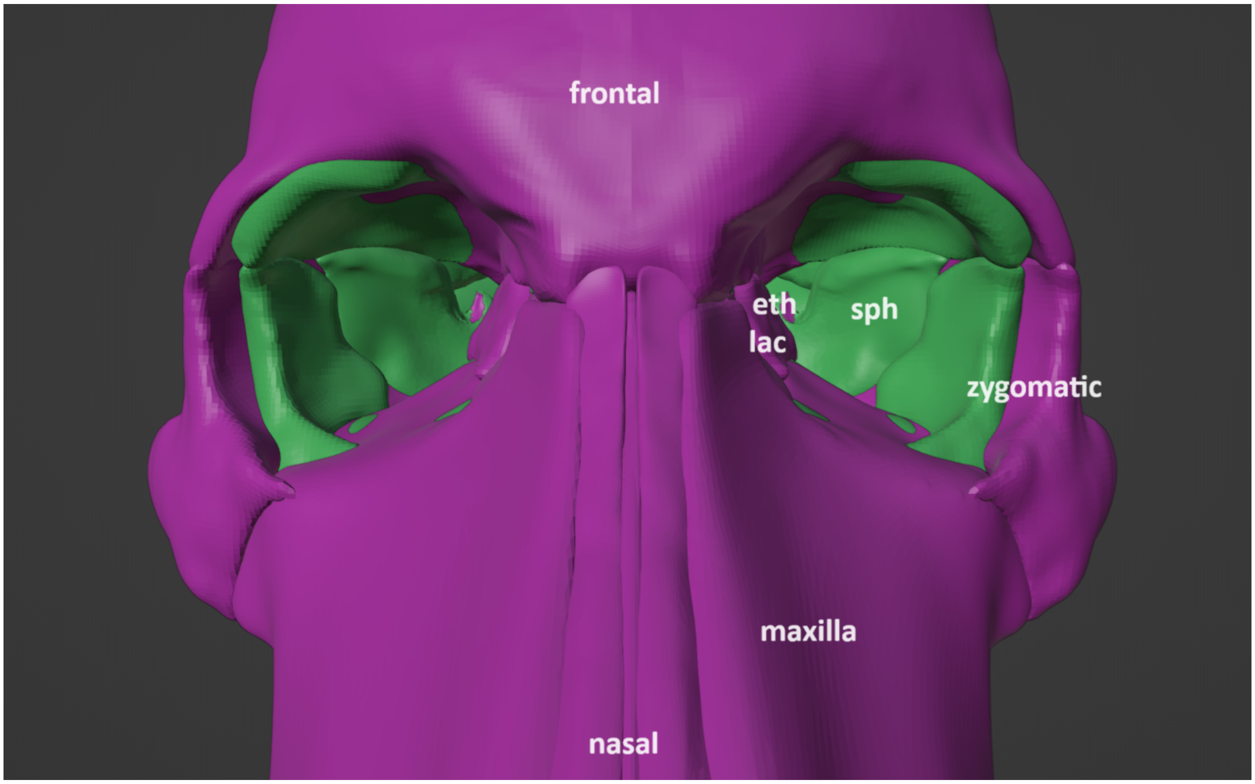
At least in my analysis, it appears that the underside of the temporal, sphenoid, and occipital bones do not need modified for a successful anthropomorphic transition. These results may reduce the complexity of any surgeries or manipulations being considered. Please note that this is still preliminary, and Lathreas will attempt to reproduce Zennith's results especially for this area.

Overall, the regions that appear most important to achieving anthro anatomy generally are not so constrained by complex overlying tissue. Basically, modifications to the maxilla (and vomer, ethmoid plate, nasal bones, and some parts of the inferior nasal concha), mandible, exterior of the frontal bone, and orbits appear largely (or perhaps, completely) sufficient. That's still a lot - I don't want to imply it's trivial - but those areas are more superficial and interact in simpler ways with physiological processes.

Orbit modifications still bring with them a challenge - chances are, we'll need to lengthen the optic nerves - but the optic nerves, as with any living, soft tissue, will accommodate gentle strain to grow over time. Specifics including a safe growth rate, and whether genetic or growth factors are beneficial, will be investigated in the future. But, as someone who has previously worked with the far-smaller eyes and optic nerves of mice, I understand this is a relatively accessible area for surgery. Not risk-free - the optic nerves are somewhat delicate despite their sheaths - but it's possible to manipulate the area precisely with sufficient caution, tools, and skill.

Photorealistic modeling

Photorealistic modeling is crucial for the process of developing these anatomical models. Toony graphics and approximated details allow for problems to sneak in, because



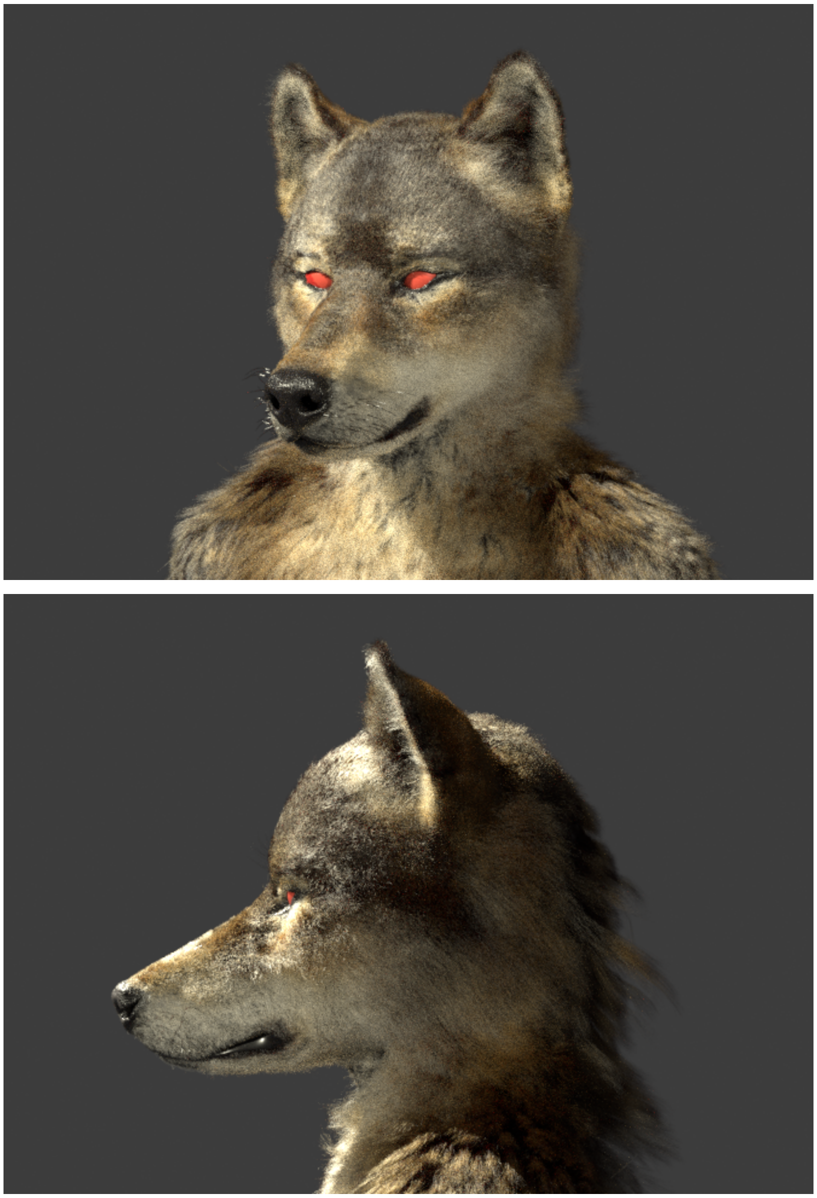
Comparison of human and anthro orbit anatomy. Anthro bones are in magenta; human bones are in green. Anthro orbits are wider, and slightly anterior, compared to how they are in humans. This implies that the zygomatic bones will be moved laterally; that the orbital surface of the ethmoid will be thicker; that the lacrimal bones will be moved laterally; and that the orbital surface of the greater wing of the sphenoid will be reduced. Slight changes in the orbital surfaces of the maxilla and frontal bones will also be needed. Abbreviations: eth = ethmoid; lac = lacrimal; sph = sphenoid.

ultimately, the results will be evaluated in real life. The "uncanny valley" could pop up for any number of reasons: incorrectly shaped muzzle, eyes too far up or down, or with the wrong distance between them, eyebrows misshapen, or incorrect proportion of the muzzle versus the rest of the head, just to give a few possible causes.

Lathreas has been letting me borrow their wolf skin model, that we've written about and shared images of before. I adjusted their model to fit the more-important constraints in my bone model, and I also adjusted the bones in my model, especially the maxilla and mandible, to fit the more visually-impactful areas of their model. Please ignore the ~~demon eyes~~ texture error!

This isn't perfect; I've been staring at the model for a long time now and would probably need fresh eyes to catch new issues. But, I think this creature looks darn good. I think if I saw them in the street, I think they'd be an (easily) passing wolf.

Lathreas is independently doing a similar thing: aligning their wolf skin model and the individually modeled bones. Honestly, they'll probably get something that looks better than mine (and they also know how to work with textures and particles better than I do!)



Renders of a wolf skin model, modified from Lathreas's original, to match bone shapes being proposed in Zennith's model.

Importantly, Lathreas is independently performing a similar analysis and this will permit us to choose optimal decisions that either researcher chose throughout their work.

Based on what they come up with in the coming days, we should be able to pick out our favorite parts of each version, and make more educated, semi-final guesses about which specific bones need modified, and by how much. We should soon get to an aligned, common model that was arrived at through two researchers working independently.

And then what?
After we get our models aligned, what's next?

Well, the head anatomy video(s), most immediately. But *then* what?

This modeling, again, is intended to do a lot. It's how we're figuring out which exact anatomical changes are needed to create anthros in real life - and whether a given tissue does, or does not, need changed, can impact our choices in research projects.

For example, early in our research, before we had learned about vertical auditory canals, we were concerned we would need to figure out how to move the inner ears upwards - somehow maneuvering the vestibulocochlear organ upwards, past the brain's temporal lobes - to line up with ears on top of the head. Thank goodness we don't have to do that!

We have been gaining an understanding of the types of tissue movements needed, and their complexity. We've been balancing physiological needs, surgical complexity, likelihood of fulfilling patient goals, and gaining a sense of what our research will need to look like for head anatomical changes in the coming years.

Simultaneously, we are integrating this work into our Anatomy Reengineering Framework, so that future edits, more precise muscle modeling, and bone and muscle modifications needed to represent different species, and greater ability to represent patient-specific changes, can be designed with more computational/programmatic support.

And ultimately, we aim to develop relationships with surgeons with the appropriate skills and supportiveness of patient goals. By anticipating and resolving challenges and concerns that surgeons would likely think of, and bringing up specific suggestions and relevant concerns of our own, we could help get the relationship off on the right foot.